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Wall slope effects on the vertical pull-out capacity of tapered suction caissons

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Abstract Suction caissons offer certain advantages over other underwater foundation systems by virtue of large bearing capacity, ease of installation, and efficiency. They are typically built with upright walls. The behaviour of upright suction caissons in regard to their applications, installation, load-bearing, etc. has already been investigated by a number of researchers. However, the performance of tapered suction caissons has not been formerly studied. This paper addresses the pull-out capacity of tapered suction caissons under vertical pull-out loads. A numerical approach was used. The finite element model was first calibrated against available test results on upright suction caissons and then used to simulate the pull-out of tapered caissons. It is admitted, however, that further validation of the model against experimental results on tapered suction caissons will increase the acceptability of the results. It was observed that positive wall slopes may noticeably improve the pull-out capacity. A change from local to global failure modes was postulated as the main reason for this improved resistance. With negative wall slopes, however, the pull-out capacity slightly decreased. In addition, effects from the caisson wall slope were investigated for a number of caisson geometries, drainage conditions and soil properties.

1. Introduction

As offshore exploitation fields are steadily being pushed into deeper waters, more innovative structural and foundation solutions are required. Suction caissons have successfully been used in the past two decades with a variety of offshore structures, particularly in deep waters. Suction caissons typically have a large diameter, with a length to diameter ratio ranging from 1 to 12. They are installed by applying a suction pressure inside the caisson, which acts as an external surcharge to push the caisson into the sea floor. They may be retrieved later by applying a positive pressure inside the caisson [1].

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Conventional suction caissons have upright walls. The pull-out capacity of upright suction caissons has been investigated by different researchers using analytical (e.g., [1–6]), experimental [1,7] and numerical (e.g., [2,8–11]) approaches. Upright suction caissons and anchors have already been employed under a variety of sea bed conditions, from sand deposits to soft and stiff clays [5]. The performance of Tapered Suction Caissons (TSCs) has received limited attention in the literature [12–16]. These researchers used numerical and experimental approaches to address the installation of tapered suction caissons. They quantified and reported the extra forces necessary to install a tapered suction caisson, as compared to those for a corresponding upright one.

Tapered driven and drilled piles have been utilized on some occasions for foundation systems [17–20] to benefit from their extra load-bearing capacities, stiffer axial response and low vibration [21]. An additional vertical load (compression) capacity for tapered piles in the order of around 20%–30% (Rybnikov [17] from field tests) and 250% (Zil'berberg and Sherstnev [18] from centrifuge tests in sand) were reported. In all these cases, the pile was tapered inwards to maximise the side-resistance component. This increased installation loads as the diameter increased with penetration.

This paper addresses the response of TSCs under vertical pull-out loads (the reverse of the above mentioned tapered pile

Nomenclature

c	Soil cohesion
φ	Soil friction angle
ψ	Dilatancy angle
D	Caisson diameter
L	Caisson length
L/D	Aspect ratio
P_{uu}	Ultimate pull-out capacity of the equivalent upright suction caisson
P_{ut}	Ultimate pull-out capacity of the tapered suction caisson
s	Wall slope of the tapered suction caisson
α	Rate of enhancement in the pull-out capacity
t	Caisson wall thickness
LL	Liquid Limit
LI	Liquidity Index
R_{int}	Soil–caisson interface coefficient
c_u	Undrained cohesion
S_r	Degree of saturation
γ	Soil wet unit weight
G_s	Soil specific gravity
k	Soil permeability
$\gamma_{d\max}$	Soil maximum dry density
$\gamma_{d\min}$	Soil minimum dry density

concept). Results from the current study reveal that the TSCs exhibit noticeable pull-out capacities, compared with those from their corresponding traditional upright caissons.

2. Model outlines

2.1. Generals

The commercially available PLAXIS finite element program [22] was used to examine the behaviour of TSCs under pull-out loads. Owing to the problem geometry, a two-dimensional axisymmetric model was employed (Figure 1). The radius and depth of the soil model were about 8–10 times that of the corresponding dimensions of the caisson. The vertical boundary line had a horizontal fixity ($ux = 0$), while the lower horizontal boundary line had a full fixity ($ux = uy = 0$). Six-noded triangular elements, which use three Gaussian integration points and provide a second-order interpolation for displacements, were considered for the soil body. The caisson itself was modelled using six-noded triangular elements and non-porous linear elastic materials.

No ring or longitudinal structural stiffeners were considered in the caisson wall. This is in line with that considered by a majority of researchers who addressed the behaviour of suction caissons (see e.g., [4,10]). The behaviour of stiffened suction caissons has already been addressed by other researchers (see e.g., [23]).

A Mohr–Coulomb elasto-plastic model was used to describe the non-linear behaviour of the soil medium. This is a relatively simple plastic model, but it provided reasonable correlations with experimental results. Three plastic potential functions were also employed in conjunction with the Mohr–Coulomb yield model. They incorporated the dilatancy angle (ψ) to model the positive plastic volumetric strain increments (dilatancy), as observed with dense soils. This type of non-associated plasticity model was only introduced to sand models possessing friction angles greater than 30° (with $\psi = f - 30°$ as proposed by Bolton [24]). It is noted that dense sands with relatively high friction angles are likely to experience dilatancy behavior. This type of sand was considered in parametric studies reported in the current paper. The soil modulus of elasticity is considered to be around 1.5 to 2.5 MPa for clay, and 20 and 50 MPa for sand models. The elastic modulus for the caisson material sufficiently exceeded that of the soil.

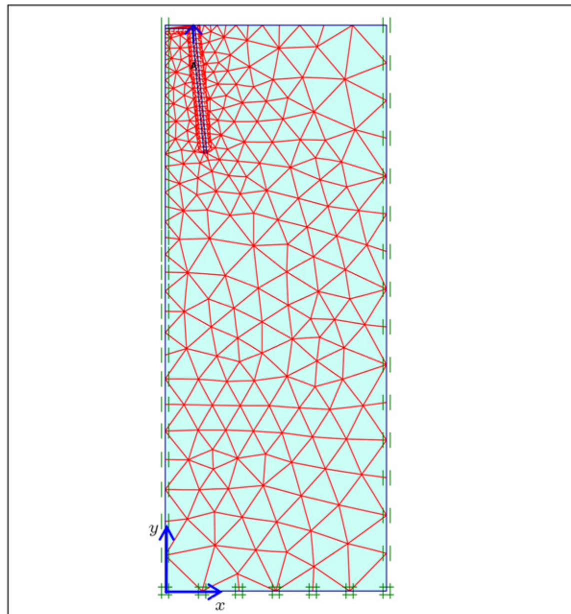

Figure 1: A typical finite element mesh and its boundary conditions.

For soil-structure interactions, a frictional contact algorithm was used. This follows a slide-line formulation that allows large relative displacements between the caisson wall and its adjacent soil elements. Interface elements were placed all around the caisson, i.e. wherever the caisson and the soil met each other, to enable a full interaction. The roughness of the interaction or the strength reduction factor (R_{int}) in the interface related the interface strength (wall friction and adhesion) to the soil strength (friction angle and cohesion), and characterized an elastic-plastic model for soil-structure interactions. The Coulomb criterion was used to distinguish between elastic behaviour (stick), where small displacements can occur within the interface, and plastic interface behaviour (slip). Both gapping (i.e. relative displacements perpendicular to the interface) and slipping (relative movement parallel to the interface) were allowed to occur.

To avoid the use of an excessively complex model that may in turn make the interpretation of the results more difficult, the soil mechanical properties were assumed to be unaffected by the caisson installation. In other words, the caissons were considered in an in situ condition prior to the pull-out simulation started (also see Section 4). It is acknowledged that in practice, the pull-out behaviour of a suction caisson is influenced by the events during and after its installation. If the caisson is installed in clay, then the clay is remoulded during installation and side shears are reduced in accordance with the sensitivity of the clay. Some parts of the original strength are subsequently regained during consolidation, prior to application of tensile loading. For sands, there should be at least a small amount of dissipation of pore-water pressure during installation, which presumably changes the properties of the sand and the normal stresses on the caisson walls. With numerical simulation of the caisson installation process, the post-installation lateral stresses between the caisson and the soil, especially on the inside, depend on whether a priori assumption is made regarding the path of penetration or the consistent update of the path of penetration as the installation of the caisson progresses [8].

Initial stresses were simulated in a gravity-loading step. A load-advancement number of step analysis types, which are recommended for cases with possible failure conditions, were used. This was a non-linear incremental small displacement type of analysis, which allows large displacements (gapping and slipping) to occur with respect to the predefined interfaces. It should be mentioned that no re-meshing scheme was adopted in the current study, and large deformations in the model were dealt with by gapping or sliding, with respect to the interfaces.

Both drained and undrained conditions were modelled so, a fully coupled pore pressure-displacement simulation was necessary. Undrained conditions represent situations where, during the pull-out, the caisson cap remains closed and the load has a short-stay nature. An undrained analysis is an instantaneous elasto-plastic calculation. During the undrained elasto-plastic analysis, excess pore pressures produced at each load increment in the soil body were computed. The behaviour was thus modelled in an effective stress approach, with explicit distinction between effective stresses and (excess) pore pressures [22]. Drained conditions represent situations where, during the pull-out, either the caisson cap remains unlocked or the load has a long-stay nature. With these models, no excess pore pressures were produced by loads applied to the system.

In fact, a drained simulation represents a very slow pull-out in which the excess pore water pressure within the soil body will be zero. An undrained simulation, on the other hand, represents a very quick pull-out, which will cause the excess pore water pressure to generate during the uplift. Time dependent effects, i.e. examining different pull-out rates between the two above mentioned limiting cases, are not considered in the current study. This is firstly because the main focus of this paper is the caisson wall slope effects. Secondly, the results for the partially drained models (pull-out rates between the two above mentioned limiting cases) will inevitably fall between the results for drained and undrained simulations. The subject has been, however, addressed by other researchers (see e.g., [2]).

2.2. Model calibration

Laboratory test data from the work of Rao et al. [25], El-Gharbawy and Olson [26] and Iskander et al. [27] were used for the calibration/validation of the numerical model. These experiments were carried out on upright suction caissons.

Rao et al. [25] carried out 1-g model pull-out tests on suction caissons with different aspect ratios in soft clays. Caisson dimensions and soil properties in three series of their experiments were:

$D = 75$ mm, $t = 3$ mm,

$L/D = 1.0$, 1.5 and 2.0, $LI = 0.4$, 0.6 and 0.8,

$c_u = 1.8$, 3.6 and 5.8 kPa,

$S_r = 0.95$, 0.96 and 0.97,

$\gamma = 16.4$, 16.45 and 1.67 kN/m^3,

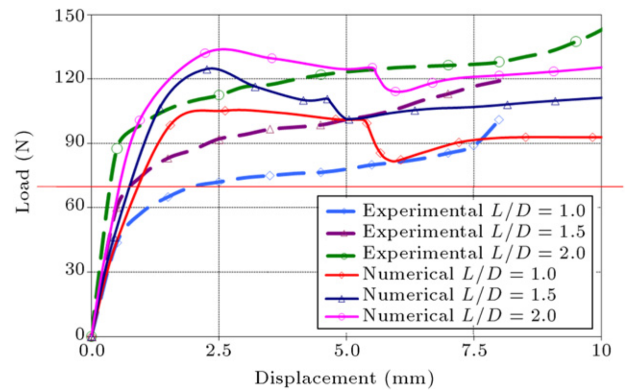

Figure 2: Numerical (from this study) and experimental (from Rao et al. [25]) results for upright suction caissons of 75 mm diameter in soft marine clay under undrained conditions.

Drainage conditions: Undrained.

More details on El-Gharbawy and Olson [26] and Iskander et al. [27] tests in clay and sand, respectively, are provided in Sections 3.1 and 3.3.

For simulation of the experiments of Rao et al. [25] with soft clays, a Mohr–Coulomb plastic model was used. PLAXIS offers the so-called Soft-Soil-Creep model for soft clays, but this model tends to over-predict the range of the elastic behaviour of soil. When an unloading path is expected (Figure 2), the Soft-Soil-Creep model hardly supersedes the Mohr–Coulomb model [22]. Results for the calibration/validation of caissons in clay only, not those in sand, are reported here.

Figure 2 presents the numerical (from the current study) and experimental (from [25]) pull-out results for caissons with aspect ratios 1, 1.5 and 2. The figure shows a relatively reasonable agreement between the pull-out capacities predicted by the numerical models and those of corresponding experiments. However, with respect to the load-bearing path, the experimental and numerical results are not in complete agreement. The experimental data in Figure 2 show a monotonic increase in the capacity for all three geometries. The numerical predictions demonstrate: (i) an initial monotonic increase in capacity, which is larger than the corresponding experiments, (ii) a drop in the capacity at about 5 mm displacement, and (iii) a subsequent increase in the capacity. The drop in capacity with the numerical responses is considered to be caused by a local tension failure at the bottom of the soil plug [28]. The subsequent increase in the capacity is believed to be caused by suction in the caisson, which increases as the pull-out proceeds. Effective stresses in the soil body are then proportionally intensified and hence after the early drop, the caisson regains resistance to the pull-out. The experimental curves appear to demonstrate similar tri-stage responses, but in a smooth pattern.

For the above reported validation attempts, the roughness of interaction or the strength reduction factor (R_{int}) between the soil body and the caisson skins (see Section 2.1) was used as the calibration parameter. The soil properties remained the same in both numerical and experimental models. With models in clay, a value of $R_{int} = 0.5$, and with models in sand $R_{int} = 0.4$ were found to maintain a relatively acceptable degree of consistency between numerical and experimental results.

In general, from the above mentioned results and other validation attempts, relatively reasonable agreement was judged between the pull-out capacities predicted by the numerical and experimental models of upright suction caissons.

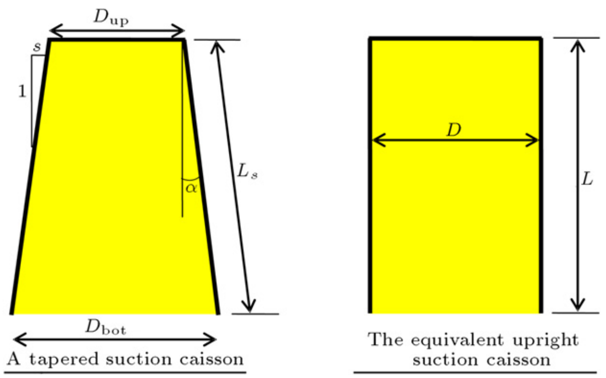

Figure 3: A tapered suction caisson and its equivalent upright caisson.

3. Wall slope effects on the pull-out capacity

This section deals with the pull-out capacity of tapered suction caisson models. The results are grouped into four basic categories:

- For TSCs in *clay* under *drained* conditions;
- For TSCs in *clay* under *undrained* conditions;
- For TSCs in *sand* under *drained* conditions;
- For TSCs in *sand* under *undrained* conditions.

With each category, different positive, negative and zero slopes were introduced to the caisson wall. The wall slope was kept below 20%. Results obtained for tapered suction caisson models were also compared with those of an equivalent upright caisson. Dimensions of the equivalent upright caisson (Figure 3) are:

$$D = \frac{D_{up} + D_{bot}}{2}, \tag{1}$$

$$L = L_s \cos\alpha. \tag{2}$$

3.1. Category No. 1: TSCs in clay under drained condition

Numerical models used for this category are based on the experiments of El-Gharbawy and Olson [26]. They conducted 1-g pull-out, as well as cyclic tests on upright caisson models with different aspect ratios (2–12), in kaolin clays under drained and undrained conditions. Caisson dimensions and soil properties in their tests were as follows:

$D = 100$ mm, $t = 3.125$ mm,

$L/D = 2$ to 12, $\varphi = 27.8^\circ$, $PL = 27\%$,

$LL = 57\%$, $c = 0.8$ kPa.

In Figure 4, typical pull-out responses of tapered suction caisson models in clay under drained conditions are given. The figure also gives the experimental (from [26]) and numerical results (from current study) for an equivalent upright caisson. As may be noted, the numerical model over predicted the ultimate experimental pull-out load for the upright caisson by around 16%. Figure 5 is a re-plot of Figure 4, in which the ordinate gives the non-dimensional pull-out capacity of tapered caissons (P_{ut}/P_{uu}). The abscissa displays the caissons wall slope (s). In this case, P_{uu} or the pull-out capacity of the equivalent upright caisson was 180 N.

In Sections 3.1.1–3.1.2, some general characteristics for the pull-out performance of tapered caissons are discussed along with results for the first category.

3.1.1. Discussions

(a) *The enhancement rate.* Results given in Figure 5 were correlated against the below trendline:

$$P_{ut}/P_{uu} = 1 + \alpha s^n, \tag{3}$$

where α is the coefficient introduced in this study to quantify the pull-out capacity enhancement caused by the slope of the caisson wall (henceforth, called enhancement rate). The enhancement rate (α), as noticed later, varies with soil type and properties, drainage conditions, and caisson penetration in the soil.

With all negative and a majority of positive wall slopes, the pull-out capacities of the tapered caissons were reasonably well-represented with a linear trendline ($n = 1$ in Eq. (3)). With positively tapered caisson models in clays under drained conditions (e.g. Figure 5), however, a non-linear relationship was more pertinent (say $n = 0.57$ in Eq. (3)).

(b) *Positively TSCs*. From Figures 4 and 5, the significance of even small positive wall slopes on the pull-out capacity of TSCs is quite clear. For example, a slope of 0.05 has enhanced the pull-out capacity by an order of about 3. The main reason behind this substantial improvement in the pull-out capacity of the positive TSCs, compared with that of the equivalent upright one, seems to be a change in their corresponding failure mechanisms.

Under vertical pull-out loads, in addition to the skin-tangent stresses, the surrounding soil blocks the upward movement of a positively tapered caisson. This triggers the resistance on a soil wedge around the caisson, and shifts the failure from local to a more extended global mode. This is a key factor for augmentation of the pull-out capacity of the tapered suction caisson, compared with that of the equivalent upright caisson. However, the soil plug inside a tapered suction caisson may either stay in place or stick to the inner skin, depending on soil properties, drainage conditions, wall slope and embedment depth (e.g. Figures 6, 10 and 13).

Positively tapered caissons achieve their ultimate pull-out capacity at considerably higher displacements than upright caissons (Figure 4). This is also interesting from a safety standpoint.

(c) *Negatively TSCs*. Figure 5 shows that with negative (inward) slopes, the rate of enhancement (α) was small. The pull-out capacities of these caissons were slightly lower than their equivalent upright caissons. For this reason, negative wall slopes were not examined on all models.

Figure 6 compares the deformed shapes of negatively and positively tapered caisson models in clay under drained conditions. With the positively tapered caisson, the upward movement of a portion of the surrounding soil elements, along with the caisson pull-out, can be noticed (Figure 6).

(d) *Snap-through performances*. Figure 4 reveals a load drop (or softening behaviour) at the early stages of all pull-out responses. With caissons of negative wall slopes, the inception of the load drop virtually marks the caisson's ultimate capacity. The softening path ends up with an almost constant residual strength (Figure 4). Interestingly, with caissons of positive wall slope, the load drop evolves into a snap-through type response, and hence the softening performance is followed by a hardening path (Figure 4). Later, the pull-out resistance of the tapered caisson leads to much higher values than that of the threshold of the load drop and of the equivalent upright caisson pull-out capacity.

With caissons of positive wall slope, the early drop was observed to denote the onset of the soil plug separation from the

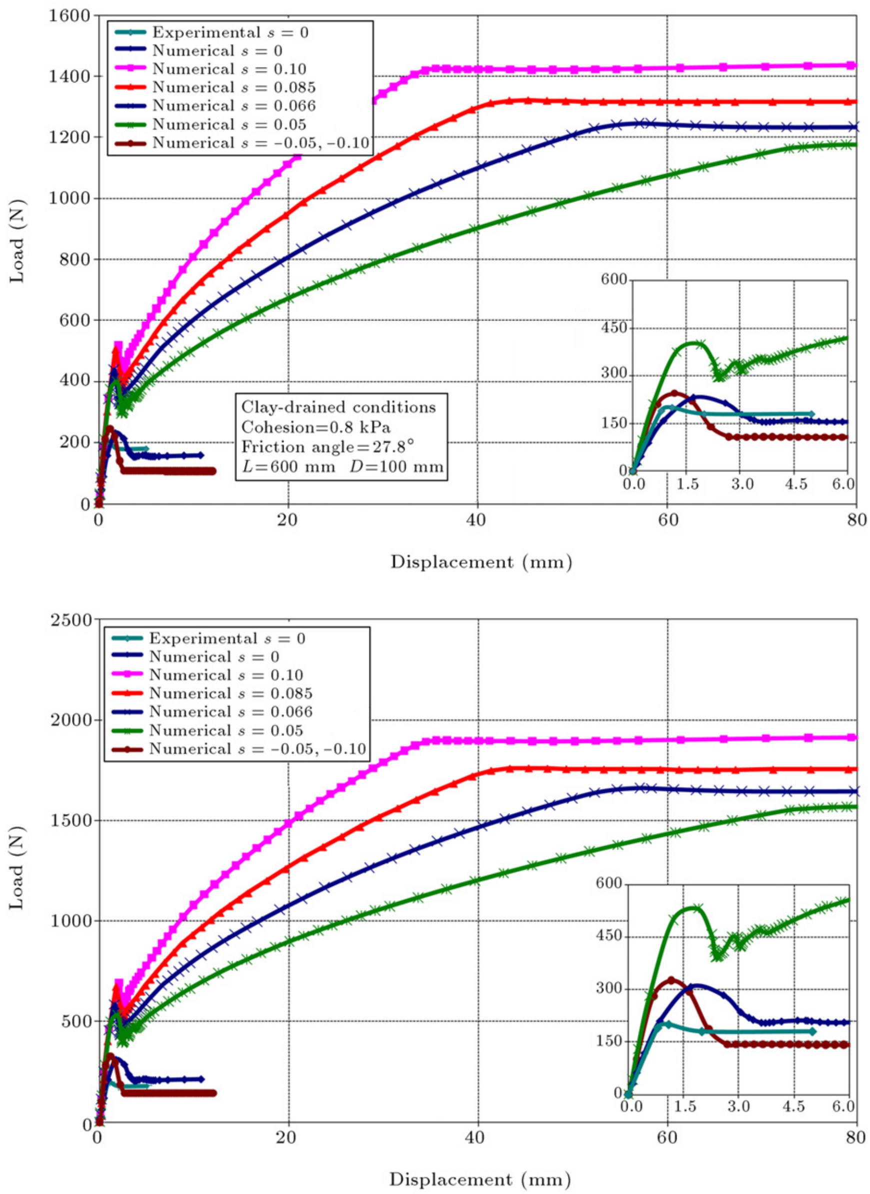

Figure 4: Typical pull-out response of tapered suction caisson models with different wall slopes in clay under drained condition.

caisson interior wall skin. As a result, the soil plug contribution to the load-bearing of the caisson progressively diminished. This demonstrated a decline path or a softening response on the load–displacement curves. However, as the caisson proceeded further upward, the shear strength on a wide wedge in the surrounding soils was mobilized. This was manifested by the post-drop hardening path, leading to a global shear failure rather than the local failure mechanisms observed with upright and negative TSCs under drained conditions [28].

It should be mentioned that with positively tapered caissons of shallow depth (penetration), the soil wedge around the caisson becomes quite small and ample global resistance is not activated. As a result, beyond the load drop, there was less significant improvement in load bearing (Figure 7).

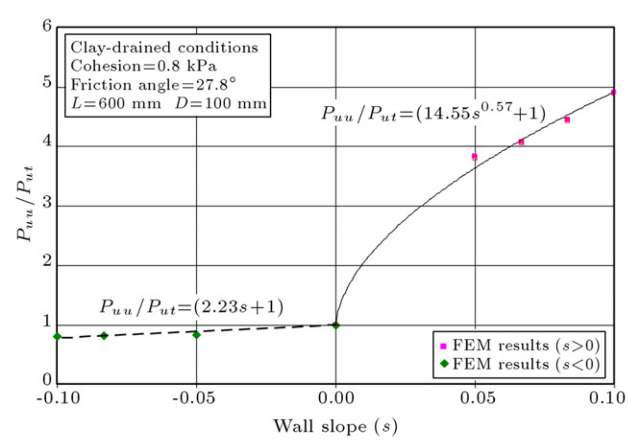

Figure 5: Variation in the pull-out capacity of tapered suction caisson models under drained conditions in clay vs. changes in the wall slope.

3.1.2. Summary of the results for category No. 1

Results for category No. 1 (TSCs in clay under drained conditions) are summarized in Table 1. The soil mechanical

Table 1: Enhancement rates (α) for different tapered caisson models in clay under drained conditions.

	Cohesion (kPa)	φ (degrees)	L (mm)	D (mm)	L/D	α	
						Positive slopes ($n = 0.57$)	Negative slopes ($n = 1$)
1	0.8	27.8	600	100	6	14.55	2.2
2	10	27.8	600	100	6	9.52	2.9
3	100	27.8	600	100	6	0.25	0.8
4	1	20	600	100	6	9.03	1.3
5	1	35	600	100	6	21.7	1.9
6	1	40	600	100	6	25.26	2.1
7	1	27.8	100	100	1	2.01	–*
8	1	27.8	300	100	3	4.23	–*
9	1	27.8	400	100	4	7.25	–*
10	1	27.8	600	120	5	19.11	–*
11	1	27.8	600	200	3	7.22	–*
12	1	27.8	600	400	1.5	4.46	–*

* Negative wall slopes have not been examined in these cases.

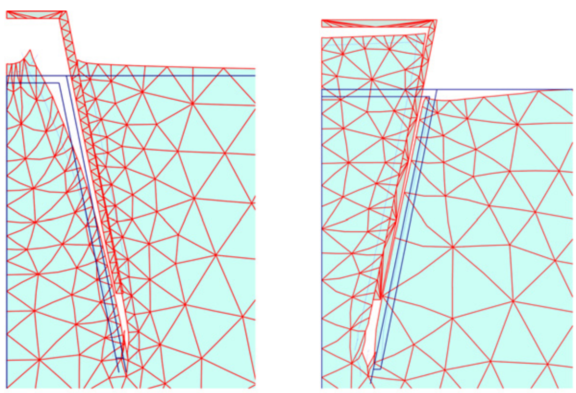

Figure 6: Deformations of positively (left) and negatively (right) tapered suction caisson models in clay under drained conditions subjected to vertical pull-out loads.

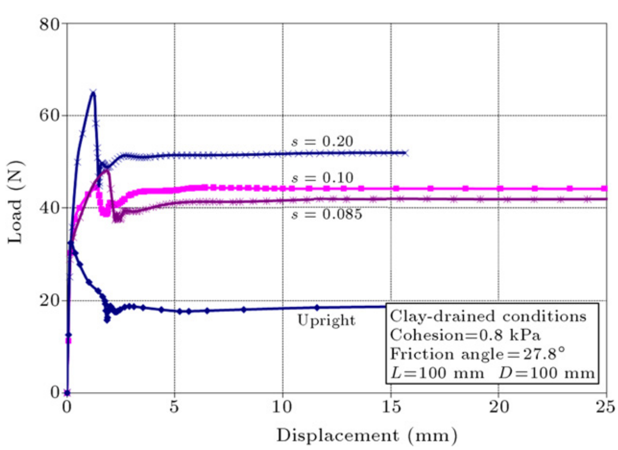

Figure 7: Typical pull-out response of a shallow TSC model ($L = 100$ mm, instead of $L = 600$ mm as in Figure 4) with different wall slopes in clay under drained conditions.

properties for the first row show typical values in experiments from El-Gharbawy and Olson [26]. With other rows, soil cohesion, the soil internal friction angle, caisson length or caisson diameter varied around their typical experimental values. Rows 1, 2, and 3 in Table 1 show that as cohesion (c) increased, α decreased. With relatively high soil cohesion (row 3 in Table 1), α was turning quite low. This means that, in this case, while the pull-out capacity of the tapered caisson remained still higher than that of the equivalent upright caisson, the degree of improvement was not substantial. Reduction in the pull-out capacity, with high values of soil cohesion, was already reported for numerical models of upright suction caissons under drained conditions [9].

Results in Table 1 show that the soil friction angle, f, had an increasing effect on the enhancement rate (α) and consequently on the pull-out capacity (rows 1, 4, 5 and 6). Caisson length (penetration) had also a marked effect on the enhancement rate (rows 7, 8, 9, and 1). It means that with longer caissons, the improvement caused by the wall slope became more significant. For instance, with a model 100 mm in length, and a wall slope of +10% (row 7), P_{ut} was 54% higher than the corresponding P_{uu}. With the same caisson, but with a depth of 600 mm (row 1), P_{ut} was around 390% higher than P_{uu}.

Table 1 shows that when the caisson length (penetration) remained constant, but caisson diameter increased, the enhancement rate (α) initially went up, but subsequently started to decrease (rows 1, 10, 11, and 12).

Enhancement rates (α) in Table 1 range from about 1 to 2 for caissons of negative wall slopes (inward slopes). For caissons of positive wall slopes, the mean enhancement rate is around 10, and its maximum exceeds 20.

3.2. Category No. 2: TSCs in clay under undrained conditions

In a similar approach to that explained in Section 3.1 of this paper, tapered suction caisson models in clay were examined under undrained conditions. The model geometry and characteristics were kept close to those used in the experiments of El-Gharbawy and Olson [26].

Typical load–displacement curves are given in Figure 8. In this figure (and later in Figure 14), an initial almost linear response is followed by a non-linear path. This, then, turns into an almost linear hardening track. The pull-out capacity in Figure 8 was chosen as the minimum of two loads: (i) at the intersection of lines overlying the initial and the hardening paths and (ii) at a displacement equal to 0.25 L, as recommended by Rao et al. [25]. A linear trendline ($n = 1$ in Eq. (3)) represented the normalized capacities reasonably well (Figure 9).

Results from TSC models studied under undrained conditions in clay are summarized in Table 2. It is clear that with positive wall slopes, the pull-out capacity was considerably improved. For example, a TSC with a wall slope of +10%, demonstrated a pull-out capacity around 2.8 times higher than that of its equivalent upright caisson (row 6). Nevertheless, under

Table 2: Enhancement rate (α) for different tapered caisson models in clay under undrained conditions.

	Cohesion (kPa)	φ (degrees)	L (mm)	D (mm)	L/D	α	
						Positive slopes ($n = 1$)	Negative slopes ($n = 1$)
1	0.8	27.8	600	100	6	22.7	4.8
2	10	27.8	600	100	6	21.0	4.8
3	100	27.8	600	100	6	11.1	3.0
4	1	20	600	100	6	17.1	4.5
5	1	35	600	100	6	25.6	5.1
6	1	40	600	100	6	27.6	5.1
7	1	27.8	100	100	1	2.0	–*
8	1	27.8	300	100	3	9.8	–*
9	1	27.8	400	100	4	17.2	–*
10	1	27.8	600	120	5	15.1	–*
11	1	27.8	600	200	3	7.9	–*
12	1	27.8	600	400	1.5	3.9	–*

* Negative wall slopes have not been examined in these cases.

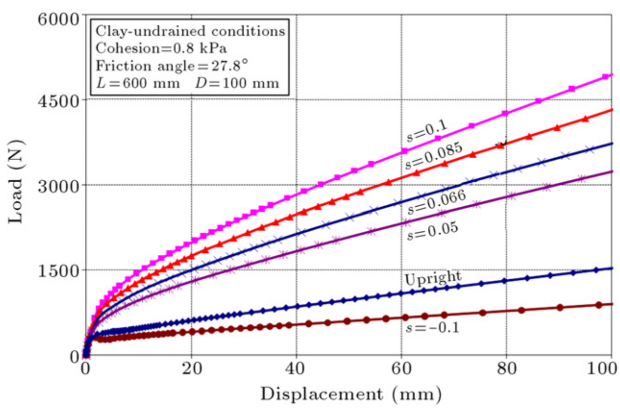

Figure 8: Pull-out response of tapered suction caisson models with different wall slopes in clay under undrained conditions.

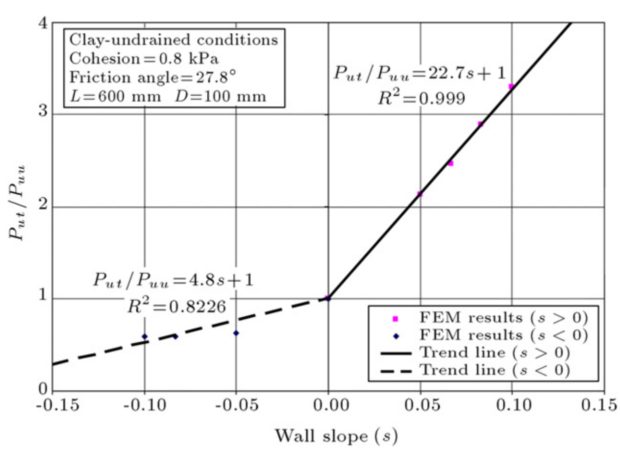

Figure 9: Variation in the pull-out capacity of tapered suction caisson models under undrained conditions in clay vs. changes in the wall slope.

undrained conditions, the enhancements were comparatively lower than those from similar models under drained conditions (Table 1).

Table 2 indicates that the enhancement rate (α) increased with an increase in the soil internal friction angle (φ) (rows 1, 4, 5, and 6). Reduction in the length (penetration) of the caissons resulted in a remarkable decrease in the enhancement rate (rows 7, 8, 9 and 1). In contrast to the models under drained conditions, the enhancement rate reduced with the widening of the caisson (rows 1, 10, 11 and 12). With respect to negative wall slopes, the enhancement rate (α) varied from around 3 to 5 (Table 2).

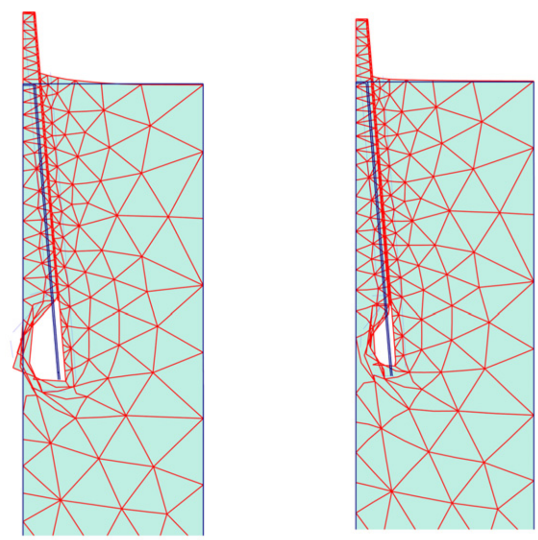

Figure 10: Deformations of tapered suction caisson models in clay under undrained conditions when subjected to vertical pull-out loads.

Figure 10 shows the deformed shape of a caisson model (row 9 in Table 2). Both a global shear failure in the soil medium around the caisson and a local tensile failure at the bottom of the soil plug can be distinguished. It is noted that a tension cut-off was considered for soil materials. The void in Figure 10 was caused by gapping (relative displacements perpendicular to the interface) and slipping (relative displacements parallel to the interface) displacements. Beyond this local tensile separation, the soil plug remained attached to the inner skin and accompanied the caisson in its upwards movement. In the majority of models under undrained conditions, the soil plug failure was noticed to be in tension (Figure 10). However, with models under drained conditions, the soil plug failure was observed to be in shear along the inner skins (Figures 6 and 13).

Another notable development regarding the undrained tapered models is the disappearance (Figure 8) of load drop or the softening performance reported earlier with the models under drained conditions (Figure 4). The load drop (or a snap-through response) was attributed to the gapping between the caisson and the soil plug. Figure 10 shows that under undrained

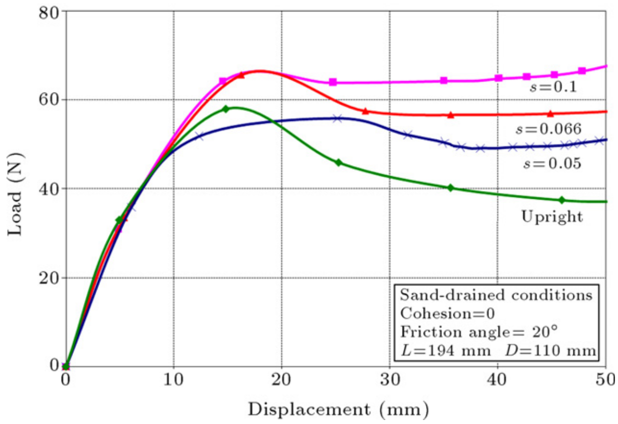

Figure 11: Pull-out response of tapered suction caisson models with different wall slopes in sand under drained conditions.

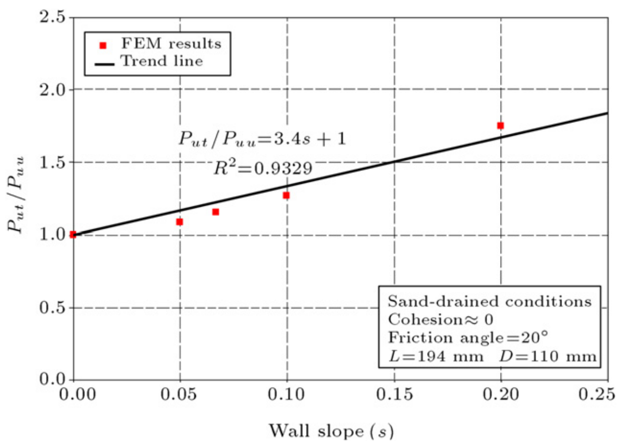

Figure 12: Variation in the pull-out capacity of tapered suction caisson models under drained conditions in sand vs. changes in the wall slope.

conditions, such gapping did not occur. This was presumably the reason for the disappearance of the early load drop from the corresponding load–displacement curves. Under undrained conditions, the suction created inside the caisson appeared to bond the soil plug to the inner skin of the caisson. With tapered caissons of higher slopes or low aspect ratios, the soil plug, however, was partially detaching from the caisson as the pull-out proceeded. Under undrained conditions, in models of very low penetrations (e.g., row 7 in Table 2), the pull-out response became identical to those under drained conditions (Figures 4 and 7). It means that the load drop turned up yet again.

3.3. Category No. 3: TSCs in sand under drained conditions

The geometry and characteristics of numerical models in this category were kept close to those in the experiments of Iskander et al. [27]. They performed 1-g tests in Oklahoma sand. Caisson dimensions and the soil properties in their tests were:

$L = 194$ mm, $D = 110$ mm,

$t = 5$ mm, $\varphi = 41°$,

$G_s = 2.65$, $k = 0.01$ mm/day,

$\gamma_{d\max} = 17$ kN/m^3, $\gamma_{d\min} = 15.3$ kN/m^3.

As per the PLAXIS manual, at least a minimum value of cohesion (say $c = 0.05 \approx 0$ kPa) must be considered for non-cohesive soils. However, slightly higher cohesion values were also examined.

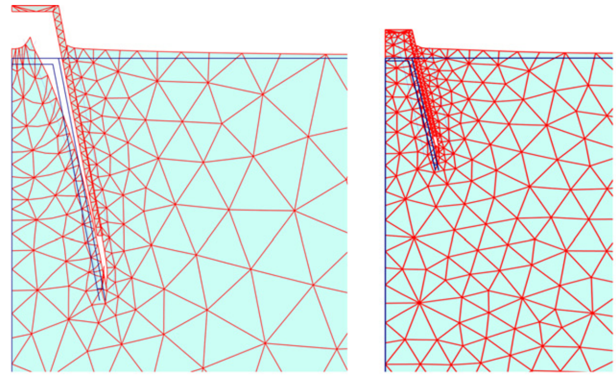

Figure 13: Deformations of tapered suction caisson models in sand under drained conditions when subjected to vertical pull-out loads.

Some typical pull-out responses are presented in (Figures 11 and 12) and extra results are summarized in Table 3. As seen, the pull-out capacity of the caisson was improved by tapering. However, the effects were far less than those observed with models in clay under drained conditions (Figures 4 and 5 and Table 1). On the whole, the values of α (in the first 11 rows in Table 3) were considerably low.

As mentioned earlier, the models in each category were intentionally maintained close to the referenced experiments. Caissons in sand [27] were considerably shorter than those in clays (El-Gharbawy and Olson tests [26]). Low rates of enhancement in Table 1 were perceived to be rooted in the small length (penetration) of the models used in this category (first 11 rows in Table 3).

To verify this judgment, models of higher penetration (yet in sand under drained conditions) were also examined. The results are given in rows 12–15 of Table 3, which show a notable increase in α values. This is because the pull-out capacity of tapered caissons is largely mobilized by a soil wedge around the caisson. With low penetrations, this soil wedge grows small and the global strength caused by the caisson tapering becomes insignificant. It can be concluded that the penetration depth of a tapered suction caisson has a distinct effect on its pull-out capacity. Owing to depth differences, results from any small-scale experiments on tapered caissons need to be justified for full-scale applications. Another outcome is that full-scale tapered caissons may show enhancement rates (α) well above the values reported in this study that followed lab-model geometries.

Following a load drop at early stages of the pull-out, shallow tapered caissons (first 11 rows in Table 3) did not demonstrate notable enhancements (Figure 11). Longer models (rows 12–15 in Table 3) exhibited a hardening path beyond an initial load drop. In this category, the pull-out capacities were in a linear approximation with the wall slope (Figure 12).

Table 3 shows that with the increase in cohesion and φ values, α initially increased and then started to decrease. However, the effects were less significant than those observed in clay models. The caissons lengthening and widening presented comparable tendencies, as reported earlier for the models in clay under drained conditions. Tapered caissons of negative wall slope showed enhancement rates (α) of about 1–3.

Figure 13 shows the pre and post failure deformed shapes of a tapered caisson model in sand under drained conditions. As

Table 3: Enhancement rates (α) for different tapered caisson models in sand under drained conditions.

	Cohesion (kPa)	φ (degrees)	L (mm)	D (mm)	L/D	α	
						Positive slopes ($n = 1$)	Negative slopes ($n = 1$)
1	≈0	41	194	110	1.76	2.9	1.3
2	1	41	194	110	1.76	3.3	3.3
3	2	41	194	110	1.76	5.8	–*
4	≈0	20	194	110	1.76	3.4	–*
5	≈0	30	194	110	1.76	4.2	–*
6	≈0	41	220	110	2	4.2	–*
7	≈0	41	440	110	4	5.8	–*
8	≈0	41	550	110	5	8.5	–*
9	≈0	41	194	39	5	4.2	–*
10	≈0	41	194	49	4	3.7	–*
11	≈0	41	194	97	2	3.0	–*
12	1	41	550	110	5	18.6	–*
13	2	41	550	110	5	14.1	–*
14	≈0	20	550	110	5	16.3	–*
15	≈0	30	550	110	5	20.5	–*

* Negative wall slopes have not been examined in these cases.

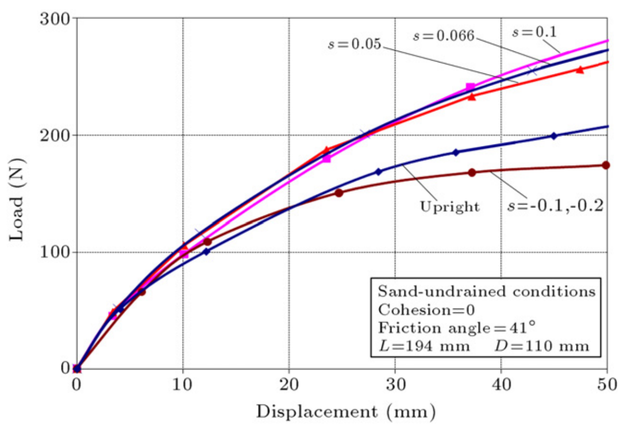

Figure 14: Pull-out response of tapered suction caisson models with different wall slopes in sand under undrained conditions.

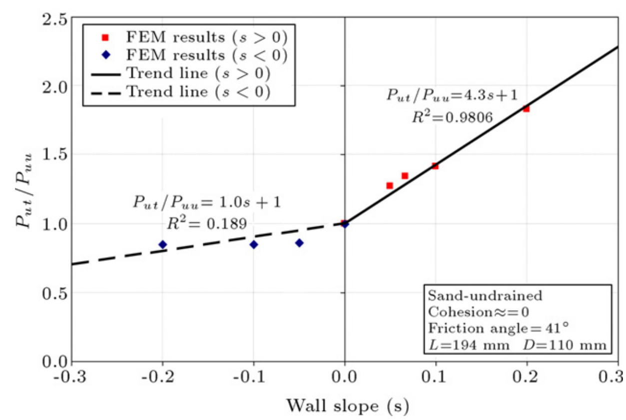

Figure 15: Variation in the pull-out capacity of tapered suction caisson models under undrained conditions in sand against changes in the wall slope.

can be seen, the soil plug remained in place (reasons given in Section 3.2).

3.4. Category No. 4: TSCs in sand under undrained conditions

Model geometry and characteristics in this category were kept close to those used in the experiments of Iskander et al. [27]. It is noted that development of an undrained behaviour in saturated sands requires very rapid loading. This can occur, for example, in a tension leg platform, where the operational waves have a period of around 8 s, and the natural heave period of the platform is around 2 to 4 s. Typical results are presented in Figures 14 and 15. It can be noticed that the load drop (Figure 11) once again disappeared from the pull-out load responses (Figure 14). This was most likely a consequence of the direct and indirect effects of the suctions developed under undrained conditions. Review of the deformed shapes of the models studied under undrained conditions indicated that the soil plug remained stuck to the caisson throughout the pull-out, even after a tensile failure developed around the bottom of the soil plug.

Further results from the tapered caisson models in sand under undrained conditions are summarized in Table 4. As can be seen, α values for caissons of positive wall slopes were less than those observed for models in clay (Table 2). This was attributed to the low penetration considered for models in sand compared to that of the models in clay. From rows 13 to 16 in Table 4, it can be perceived that the rate of enhancement (α) was noticeably increased by an increase in caisson penetration.

Table 4 shows that soil characteristics (such as c and φ) and caisson geometry (its length and diameter) influenced the enhancement rate (α) and the pull-out capacity (P_{ut}) in a similar way to that reported for the models in sand under drained conditions, but with different amounts.

4. Installation effects

As already discussed, the pull-out capacities reported in this study were for a "wished-in-place" caisson model. In other words, it was assumed that the soil around the walls of the suction caisson was regaining its full original shear strength after installation. In practice, the soil properties in the immediate vicinity of the caisson are affected by the caisson installation [3], which may be more significant with a tapered caisson. In particular, the soil on top of the sloping walls, which created the additional uplift capacity, might itself become disturbed or remoulded during the installation. To examine soil remoulding effects on the pull-out capacities of tapered caissons, for a soil wedge sitting on the walls of the caisson (Figure 16), degraded mechanical properties were assumed. Details of the new mechanical properties are given in Table 5. Values given in the table are around or below those proposed

Table 4: Enhancement rates (α) for different tapered caissons models in sand under undrained conditions.

	Cohesion (kPa)	φ (degrees)	L (mm)	D (mm)	L/D	α	
						Positive slopes ($n=1$)	Negative slopes ($n=1$)
1	≈0.0	41	194	110	1.76	4.3	1.0
2	1	41	194	110	1.76	3.6	1.3
3	2	41	194	110	1.76	2.8	–*
4	≈0.0	20	194	110	1.76	2.8	–*
5	≈0.0	30	194	110	1.76	4.2	–*
6	≈0.0	35	194	110	1.76	3.7	–*
7	≈0.0	41	220	110	2	4.4	–*
8	≈0.0	41	440	110	4	8.9	–*
9	≈0.0	41	550	110	5	9.7	–*
10	≈0.0	41	194	39	5	6.1	–*
11	≈0.0	41	194	49	4	4.5	–*
12	≈0.0	41	194	97	2	4.4	–*
13	1	41	550	110	5	15.1	–*
14	2	41	550	110	5	16.1	–*
15	≈0.0	20	550	110	5	15.0	–*
16	≈0.0	30	550	110	5	23.8	–*

* Negative wall slopes have not been examined in these cases.

Table 5: Degradations in the mechanical properties of the soil wedge around an in situ tapered caisson.

Soil type	Drainage condition	C (kPa)	φ (degrees)	E (MPa)	Dry density (kN/m^3)	Wet density (kN/m^3)
Clay	Drained	1 → 0.5	27.8 → 15	2.5 → 1.5	17 → 15	20 → 18
Clay	Undrained	5 → 3	27.8 → 15	2.5 → 1.5	17 → 15	20 → 18
Sand	Drained	–	41 → 25	50 → 30	17.9 → 15	20.7 → 19
Sand	Undrained	–	41 → 25	50 → 30	17.9 → 15	20.7 → 19

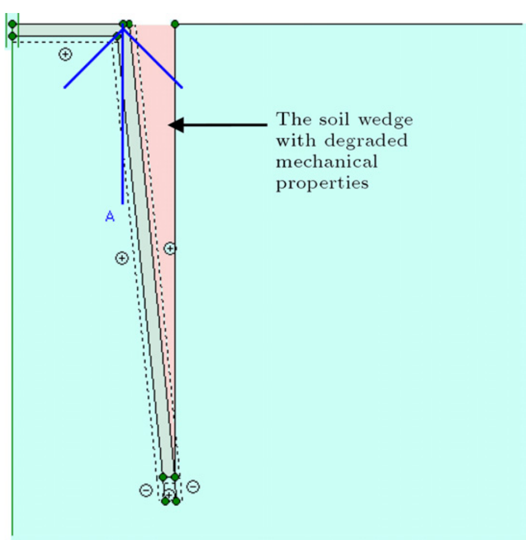

Figure 16: The soil wedge around a tapered caisson with degraded mechanical properties.

(65% of the initial strength) by Andersen and Jostad [3]. The soil properties in the remaining parts of the soil body were assumed unchanged. It is noted that a routine for choosing mechanical properties for disturbed soils is to assume a new residual friction angle, along with zero cohesion. In the current paper, an approach similar to that considered by Andersen and Jostad [3] has been used. The pull-out capacities for some models studied are given in Table 6. It can be noticed that the remoulding caused up to 21% reduction in the pull-out capacity of the TSCs. However, the pull-out capacities were still considerably higher than those of the equivalent upright caisson.

It is reiterated that results reported in Table 6 are based on an assumption that the remoulded soil area is limited to that shown in Figure 16. This is, however, an assumption that may be arguable and very difficult to verify without actual measurements and data. Installation of a TSC may greatly disturb the soil outside and inside the caisson. The soil disturbance inside the TSC appears to have little effect on the pull-out capacity. The extent of the disturbance of the soil outside the caisson, nevertheless, does affect the pull-out performance of a TSC.

5. Laboratory modeling

The effects of wall tapering on the pull-out strength of suction caissons were also examined under a 1-g laboratory physical modelling. This section provides a brief summary of these experiments and their results. The details of the experiments will be reported in a separate paper.

One upright and one tapered suction caisson, each 240 mm high, with 2.5 mm wall thickness and 80 mm outer diameter (at their mid-height), were employed in the experiments (Figure 17). The tapered caisson had a wall slope of 10%. The caisson cap was flat and 20 mm thick. The cap was fitted with a manually operated valve, which could be opened and closed in-flight. The valve acted as a water evacuation outlet during penetration of the caisson. It remained close during the pull-out phase. A penetration/pull-out device with full control of displacement was used. The caissons were tested in a steel soil box with 70 × 70 cm horizontal and 100 cm vertical dimensions. Linear Variable Differential Transformers (LVDT) displacement gauges were used to record the time series of the caisson penetration. A load cell, placed between the loading shaft and a vertical rod on top of the caisson, was used to monitor the load applied to the caisson.

Table 6: Remolding effects on the pull-out capacity of the tapered suction caisson models.

No	Soil/Caisson properties								Pull-out capacity			
									Equivalent	Tapered models		
	Soil type	Drainage condition	D (mm)	L (mm)	t (mm)	c (kPa)	φ (deg.)	Wall slope (%)	upright model (N)	Undisturbed wedge (N)	Disturbed wedge (N)	Difference (%)*
1	Clay	Drained	100	600	3.125	10	27.8	5	210	315	309	2
2		Undrained	100	600	3.125	10	27.8	8.5	520	2010	1849	9
3	Sand	Drained	110	550	5	0	41	10	1600	3240	2687	21
4		Undrained	110	194	5	0	41	10	290	390	349	12

* -Ratio of entries of two previous columns.

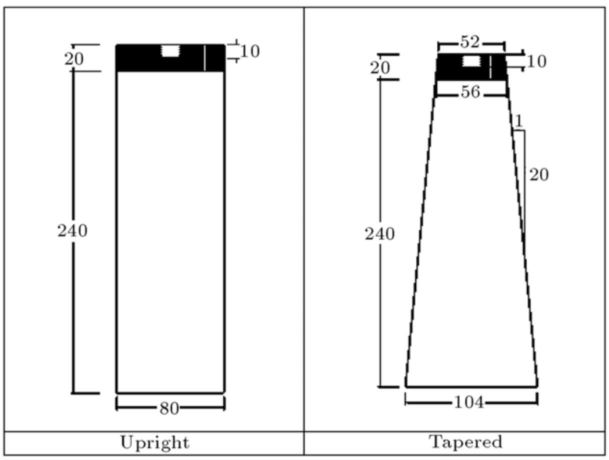

Figure 17: Views and overall dimensions of the laboratory models for the upright and tapered suction caissons.

Table 7: Soil particle size distribution.

Sieve no.	Diameter (mm)	Passing (%)
4	4.75	100
10	2	99.53
20	0.841	99.00
30	0.595	97.75
40	0.42	96.24
50	0.247	92.13
100	0.15	48.09
200	0.075	27.97

The laboratory test was performed on fine round silty sands. The particle size distribution of the soil samples is given in Table 7. Soil beds, with two different density ranges of 1.38–1.42 g/cm^3 and 1.45–1.51 g/cm^3, and internal friction angles (φ) of 26° and 28°, respectively, were prepared for these experiments. Figure 18 shows a tapered suction caisson model during the installation phase in the soil tank.

Figure 19 reports a sample result from the pull-out tests on upright and tapered suction caissons. The figure also demonstrates the pull-out rate effects on caisson behaviour. The tapered caisson had a wall slope of 10%. Both the tapered and upright caissons were 240 mm long, with an aspect ratio of 3. Two different pull-out rates of 30 and 90 mm/min were considered in these tests. The tests were carried out in dense sand.

As noticed, tapered caissons demonstrated higher pull-out capacities compared to their corresponding upright caissons (Figure 19). The enhancement in the pull-out capacity, caused by the tapering of the caisson wall, was around 33% and 57% in the rapid and slow pull-outs, respectively.

Figure 18: One tapered suction caisson is penetrating into the soil bed.

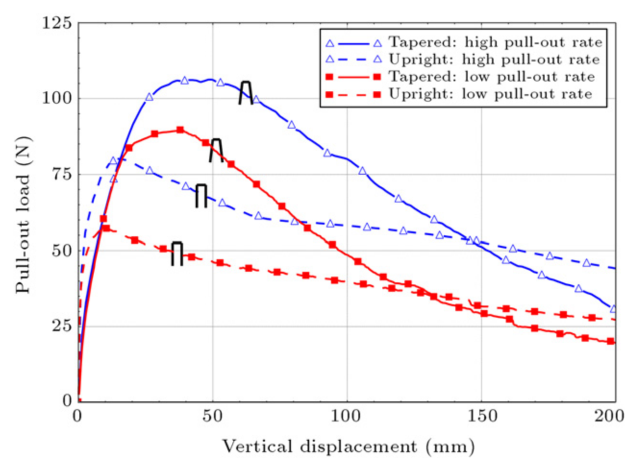

Figure 19: Load–displacement diagrams for upright and tapered suction caissons in dense sand under two different pull-out rates.

With a high pull-out rate, the load bearing capacities of both tapered and upright caissons increased (Figure 19). The corresponding increase in the pull-out capacity was around 40% for upright caissons and around 19% for tapered caissons. It means that the pull-out rate had a more pronounced effect on the load bearing capacity of the upright caisson, as compared to the tapered caisson. This can be attributed to the difference in failure modes of tapered and upright caissons, as discussed in Section 3.1.1. In fact, an increase in the pull-out rate results in intensifying the hydraulic gradients during the pull-out process. This mostly affects the soil in the vicinity of the caisson. The most beneficial effect from the increase in the pull-out rate, therefore, incorporates the local rather than global failure modes. As the pull-out response of the tapered caissons is dominated by a global failure mode, increase in the pull-out rate is expected to have less impact on their pull-out capacity, as compared to that of an equivalent upright caisson.

Figure 19 shows that by increasing the pull-out rate, the displacement corresponding to the ultimate load also increased. In other words, an increase in the pull-out rate caused the load–displacement diagram to move top-right. Wall tapering can also be seen to have had a similar effect. Introducing the wall slope to the caisson caused increases both in the ultimate pull-out capacities and in the displacements corresponding to the ultimate loads.

6. Conclusions

Tapered Suction Caissons (TSCs) have not received much attention in the literature. This paper deals with the behaviour of TSCs under vertical pull-out loads. Based on numerical simulations, and assuming an in situ condition for the suction caisson it was found that even small positive wall slopes may provide notable improvements in the pull-out capacity. A change from local to global failure modes, and resistance mobilized by a soil wedge around the caisson, were judged as key factors for the improvement in the pull-out capacity of TSCs. This is why with negative wall slopes, the pull-out capacity slightly decreased.

Wall slope effects were subsequently examined on a number of caisson geometries, drainage conditions, and soil properties. The pull-out capacity was always enhanced by positive wall slopes. Under drained conditions, enhancement in the pull-out capacity, caused by the wall slope, was generally higher than that under undrained conditions. TSCs of low penetration and small aspect ratios demonstrated lesser enhancements in their pull-out capacity.

In this study, only vertical pull-out loads were examined. This is the main load in foundations for tension leg, oil and gas platforms. Behaviour of TSCs under inclined loading (as with anchors for the mooring systems of semisubmersible or spar oil and gas platforms) and other actions, such as moments and shear loads (as for Jacket type platforms) need further investigation. It is also emphasized that the applicability of using tapered suction caissons in practice and the validity of the numerical results need further experimental and/or field investigations.

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